Spectrum Scanning and Reserve Channel Methods for Link Maintenance in Cognitive Radio Systems

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***Abstract*—Underutilization of the limited spectrum sparked the need for dynamic spectrum access and flexible spectrum policies. Accurate estimation of spectrum occupancy is an essential step for spectrum access in distributed networks. This paper analyzes a bidirectional and dual scanning method that scans multiple spectrum bands to find a suitable free-channel. Moreover, secondary users' access to available spectrum could be interrupted by the arrival of primary spectrum users, forcing the well-behaved secondary users to switch to another free-channel. A pointer and adaptive reserve channel mechanism is proposed in this paper to facilitate quicker and smoother channel switching. Simulation results for both techniques show improved overall connectivity is maintained for varying primary users' arrival rates.**

I. INTRODUCTION

High utilization and demand for certain portions of spectrum and underutilization of the remaining parts sparked the need for immediate reforms in spectrum allocation policies. Spectrum regulatory agencies such as FCC (USA), Ofcom (UK) and others in respective countries are developing strategies to improve spectrum utilization and distribution [1]. Cognitive radios (CR) are being proposed as a possible solution for sharing such unutilized or underutilized portions of spectrum, provided such a mechanism causes no interference to any primary users. Thus, spectrum that would be available for secondary users are non-contiguous frequency bands of different width distributed over a wide range of spectrum. Fundamentally, distributed cognitive radio solutions will require the ability of reliably scanning the spectrum to find a free-channel, as well as mechanisms for managing channel contention between primary and secondary users to maintain reasonable link quality. Understanding and accurately estimating the dynamic nature of spectrum channels is an essential first step.

Several channel sensing and detection techniques such as matched filter detection, energy detection and cyclostationary feature detection are analyzed for cognitive radios in [2]. In [3], it is shown how the presence of pilot signals could improve detection of undecodable signals. There are several cooperative sensing schemes where cognitive users cooperate or collaborate to mitigate false detection and improve spectrum sensing even in fading environments [4][5]. Plenty of work is being carried out on power control and channel allocation mechanisms to improve spectrum utilization. The channel allocation problems are modeled as game theory [6] and graph coloring problems [7] to optimize spectrum utilization.

However, solutions for spectrum mobility - the ability of a distributed cognitive radio to scan the spectrum and adaptively switch channels to mitigate secondary users link degradation is less explored. The need for efficient and seamless spectrum mobility is analyzed in [8]. The incumbent (primary user) arrival scenario is mentioned in [9], but the effects and solutions are not discussed in detail. The SU link maintenance through redundancy codes is analyzed in [10].

In this paper an adaptive framework which exploits the cognitive radio's capability to intelligently scan through the wide spectrum and adaptively switch to facilitate seamless spectrum access is proposed. This consists of (i) a spiral-bidirectional and dual spectrum scanning method for effectively scan wide band spectrum (ii) a pointer and adaptive reserve channel mechanism to facilitate link maintenance. Analysis of the parameters influencing efficient and fair channel allocation is also presented.

II. SYSTEM MODEL AND ASSUMPTIONS

In this model, primary users (PU) are defined as long-term licensed (priority) users and secondary users (SU) as opportunistic sharing users. The SUs sense the channels, opportunistically use the unoccupied band and exit on sensing a PU's arrival. SUs are assumed to be randomly distributed in the location considered and form a distributed cognitive network. We assume the spectrum bands that would come under such a sharing mechanism would be non-contiguous bands of spectrum. The minimum width of the non-contiguous channels is chosen such that its detection and channel estimation is accurate during channel sensing as the spectrum access relies on the validity of the spectrum sensing information. For a channel to be sensed available, the user monitors the channel for a minimum period called *detection time* Δt to estimate the occupancy nature and ensure suitability of the channel for selection. Longer Δt means spectrum usage is wasted during detection and shorter Δt would result in unreliable or even incorrect sensing.

The following assumptions are adopted in the model considered in this paper. Although the system is adaptive and could sustain sensing error, it is assumed that the channel sensing and

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detection is fairly accurate. The regulatory policy messages, neighbors sensing and allocation messages are assumed to be transmitted in specially designated *common channels*. In the RF front-end, it is assumed that the channel scanning and sensing is carried out independently of on-going communication and causes no interruption to signal transmission or reception. The channels are assumed to be a non-contiguous band of frequencies and suffer white noise throughout with different fading and interference. Thus it is assumed that each channel could offer a different capacity.

III. Spectrum Scanning methods

Accurate and effective sensing of a wide-band spectrum is a challenging problem in distributed cognitive radio networks. Assessing the dynamic nature of the spectrum and gathering reliable and sufficient information is essential for opportunistic spectrum access. A scanning mechanism controls the sequence of scanning and the portion of spectrum to be scanned, and it works in conjunction with the sensing mechanism. In a dynamic spectrum sharing network, when spectrum occupancy is non-uniformly distributed scanning multiple regions simultaneously could provide diverse and sufficient spectrum information. Conventional sequential scanning lacks the ability to find a free-channel in deeper spectrum region and may not be effective. For effective sensing over the spectrum, a bidirectional and dual scanning mechanism is proposed to search over a broader and deeper spectrum space. In distributed cognitive radio system, a system in which both the transmitter and receiver mutually cooperate to scan different portions of spectrum and share the spectrum sensing information is considered. To conserve battery power adaptively varying scanning rates are adopted.

A cognitive radio regularly searches for a free-channel during either

1) Initial channel selection: When a SU scans the spectrum for free channel for initial access
2) Unexpected channel switching: When a SU evacuates the current channel and switches to another channel due to a primary user arrival or when the channel suddenly degrades with interference

A. Bidirectional scanning method

In sequential unidirectional scanning, the radio scanner scans the channel in steps either in incrementing or decrementing order. Since the search space is limited to one direction, a unidirectional scan could miss a free channel available in the other direction and therefore does not ensure the detection of the nearest available free channel. By adopting bidirectional scanning, the scanning is performed in both directions, expanding through the spectrum space in both directions finding the nearest available channel.

Figure 1 shows the current band (band X) and the scanning methodology. With the starting frequency f_x, the center frequency of channel c_x, the bidirectional scanner scans channels on either direction. The scanning steps in either direction are selected alternatively and expand in either side as c_{x+1}, c_{x-1},

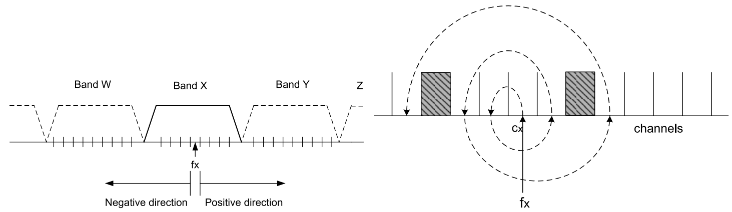

Fig. 1. Bidirectional Scanning Mechanism

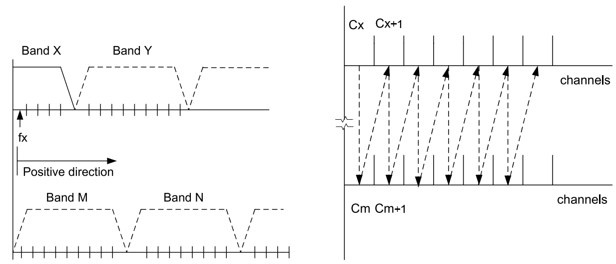

Fig. 2. Dual Scanning Mechanism

c_{x+2}, c_{x-2},... and so on, as shown in Figure 1. This alternate bidirectional scanning steps appears to be scanning in *spiral* fashion and hence may be referred to as spiral-bidirectional scanning.

B. Dual Scanning

In dual scanning, the scanner initiates scanning at two different spectrum bands, as shown in Figure 2. The starting points can be pseudo randomly selected or selected so that one is the current channel and the other is sufficiently well spaced from it within the available range. This dual scanning method combines random and sequential scanning, now capable of reaching multiple spectrum bands in a controlled manner. The spectrum bands are alternatively checked. If a free-channel is found matching the requirement, the information is mutually shared and agreed for spectrum access. The boundary conditions ensure that the same band is not scanned twice within the revisit time.

If one of the search coordinates reaches the boundary of the allowed spectrum, the searching switches to unidirectional from the other edge and continue searching. This method is called Bidir + Uni. When the spectrum occupancy is non-uniform and the current scanning region is densely occupied, then switching the scanning sequence to a distant spectrum region away from the current scanning area is an alternate option. This method is referred to as Bidir + Ran, due to the relative random jump to a different spectrum band.

IV. Reserve Channel and Link Maintenance

The crucial aspect of the spectrum allocation in distributed cognitive radio networks is how efficiently the spectrum is managed and how the SU link is maintained once the PU arrives or when the channel degrades due to interference. On the PU's arrival, one or more secondary users have to evacuate to allow the PU to regain its channel(s), causing no or minimal interference.

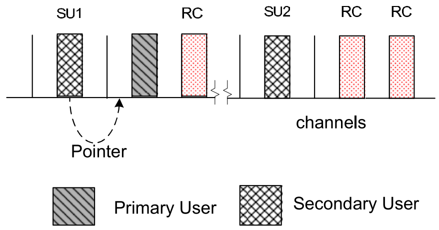

Fig. 3. Reserve Channel and Pointer in Spectrum

A. Link Maintenance for Secondary Users

Under dynamic channel conditions, every channel is susceptible to channel degradation or link termination during a PUs channel reclaim. Under such scenarios an active user may not have enough time to sense and search for free-channels and access them during transmission. The latency in sensing and detecting the free-channels and using them for SU links may cause significant loss in QoS. Since the available number of free-channels may vary considerably in this dynamic shared spectrum and every channel is susceptible to PU reclaim, it is difficult to segregate a fixed number of channels as reserve channels. Here we propose to use a Pointer and adaptive Reserve Channel (RC) mechanism to facilitate a smooth transition of SU channel occupancy, where possible. Figure 3 shows the basic illustration of Pointer and Reserve Channel in spectrum.

1) Adaptive Reserve Channel: In the proposed method not all channels in shared spectrum will be open for allocation or selection. Some channels are identified as *reserve channels* available only for maintaining links or improving the degrading links. These reserve channels are available only for SU links which are degraded or about to be disconnected and do not have any other free-channels to switch to.

The number of such reserve channels is not fixed in advance and varies proportional to spectrum occupancy and interference levels. At any time, the total number of channels available for secondary users is variable. For example, if there are 100 channels and the maximum reserve channel is 5%, then under highest channel occupancy 5 channels would act as RC. If $N_{occ}(t)$ is the number of channels occupied at time t and α is the RC proportionality variable, then the number of reserve channels $N_{res}(t)$, following linear proportional relationship is given by,

$$N_{res}(t) = \alpha N_{occ}(t)$$
$$N_{tot}(t) = N_{occ}(t) + N_{free}(t) + N_{res}(t)$$

At any time, the number of free-channels available for selection is,

$$N_{free}(t) = N_{tot}(t) - (1 + \alpha)N_{occ}(t)$$

where, $N_{tot}(t)$ is the total number of channels and $N_{free}(t)$ is number of the remaining free-channels available for access.

Further analysis and simulation has shown that exponential proportionality $N_{res}(t) = \alpha\ e^{k.N_{occ}(t)}$ could also be followed in allocating proportional number of reserve channels since higher number of reserve channels are needed at high spectrum occupancy scenarios and none are needed at low occupancy scenarios, and this is being investigated further.

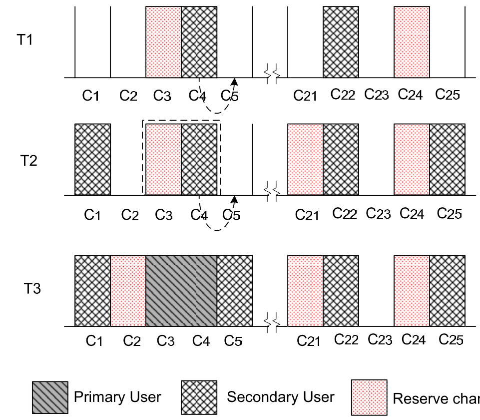

Fig. 4. Reserve channel and pointer scenario
T1: Initial condition; T2: C3 and C4 detects PU arrival; T3: Link in C4 move to C5 using pointer and RC moved to C2

A channel is not permanently segregated as a 'reserve channel' but could adaptively act as one, depending on occupancy and traffic conditions. It should be noted that channels acting as reserve channels are also susceptible for PU arrival. So any free-channel could adaptively take the role of RC and vice versa, maintaining the overall ratio of the reserved channel to total available channels.

The reserve channels are distributed over several spectrum bands to facilitate nearer switching of channels and to have least change in reserve channel conditions. In non-contiguous spectrum the user occupancy may be non-uniformly distributed. If a particular portion of the spectrum attracts more SUs, then the proportional number of RCs should be identified for that region. By identifying an increasing number of RC (linearly or exponentially) in the busy part of the spectrum it also act as a admission control for that portion and help evenly distributing spectrum occupancy.

2) Pointer: During routine spectrum scanning the cognitive radios are able to mark suitable free-channels as candidates to be occupied if the radio is required to quickly release the operating channel. This reference maintained by each CR to these candidate free-channels is called a *pointer*. A valid and updated pointer supports a smoother and quicker channel evacuation to the candidate channel. The pointer has a location address of the free-channel. The pointed channel could be the nearest available free channel or least interfered channel, found during routine scanning. The cognitive radios monitors and updates this pointer at regular intervals, as part of the channel scanning. Figure 4 illustrates a simple example. The link in C4 has a pointer to C5. At T2, when channels C3 and C4 detects PU arrival, link in C4 is subsequently moved to C5 using pointer and free-channel C2 takes up the role of RC.

B. Link Maintenance procedure using RC and Pointer

During unexpected channel reclaim by a PU or channel degradation due to interference, the SU follows the initialization protocol and occupies the pointed free-channel, if it has one. By having an updated reference pointer to the candidate free-channel, the channel transition is quicker with minimal effect on link quality. If the SU does not have a pointer or if the pointer is not updated, then the SUs temporarily occupy the nearest reserve channel (RC). The transmission in RC is allowed only for a short period of time, renewable upon request. Once any of the channels are sensed free during bidirectional or dual scan, the link in the reserve channel gets top priority to acquire the channel and the link is subsequently switched to the newly found channel. The reserve channel will then be available for any other disconnecting or degrading link. This two step combination of pointer for initial and immediate switching and reserve channel for temporary link maintenance provides seamless spectrum access and link maintenance in a dynamic cognitive radio network, as the results of the simulations reported in the following section indicate.

V. Simulation Results and Discussion

This section presents some numerical results to illustrate the performance of bidirectional channel scanning, link maintenance mechanism and the parameters affecting this performance. In this simulation, 100 channels of equal bandwidth are considered. The user arrival is modeled to be poisson with a mean rate of 5 users per interval. When SUs select a channel, the channel is given access for a time interval within a maximum lease period (*max_lease*). Each simulation was run for 100 intervals and the values were averaged over 100 such simulations.

A. Bidirectional Channel Scanning

Simulations were carried out to compare several scanning mechanisms. The parameter channel deviation is given by the relative distance between the starting channel and the free-channel found as a result of scanning. Figure 5 illustrates the channel deviation from the starting channel for different channel occupancy values. Bidir + Uni scheme ensures minimum deviation and outperforms unidirectional scanning scheme in finding the nearest free-channel. Performance is evidently better in highly occupied spectrum scenarios. Figure 6 shows the average number of steps taken to find a free-channel. The bidirectional scanning method always ensures that the nearest free-channel is found and on average, for an equal number of steps as the other mechanisms, irrespective of the spectrum occupancy.

B. Link Maintenance

The effect of reserve channel and pointers in link maintenance are illustrated in this section. Figure 7 shows a significant improvement in link connectivity if a fraction of channels are reserved as RC. We consider the disconnectivity rate, defined as the ratio of disconnected links to connected links at any given time. Even with 1% of channels as RC, the disconnectivity is improved by 77% to 0.11. Using higher values for the RC proportionality variable give better disconnectivity rates, especially for high user density scenarios. Figure 8 shows the occupancy performance for the same setup. The channel utilization remains asymptotically closer to the No-RC scenario, illustrating that the RC and pointers offer better link maintenance without compromising channel occupancy.

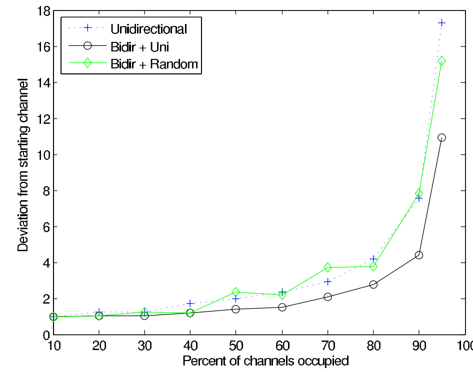

Fig. 5. Deviation from the starting channel

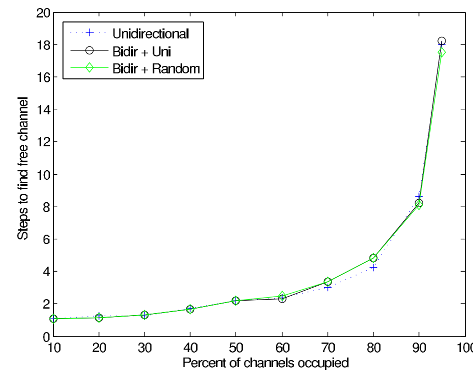

Fig. 6. Steps to find a free-channel

C. Parameters Effect on Connectivity

The link disconnectivity is affected by two parameters viz., maximum lease period and PU arrival rate. The simulations

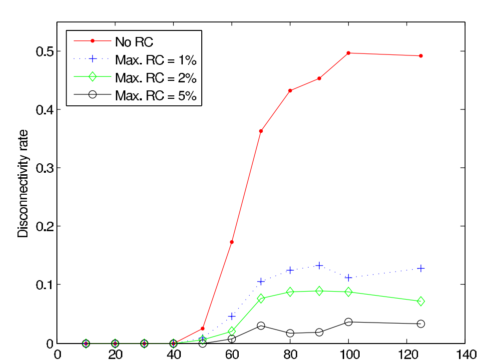

Fig. 7. Link Maintenance performance - Disconnectivity for different RC (Max lease = 100; PU arr = 5)

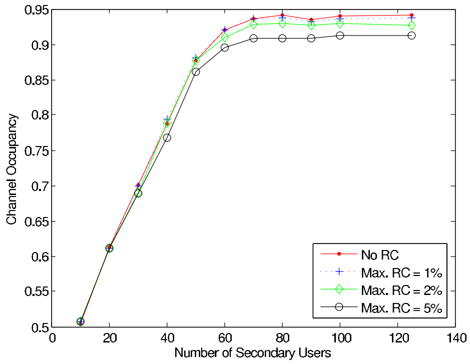

Fig. 8. Link Maintenance performance - Occupancy for different RC (Max lease = 100; PU arr = 5)

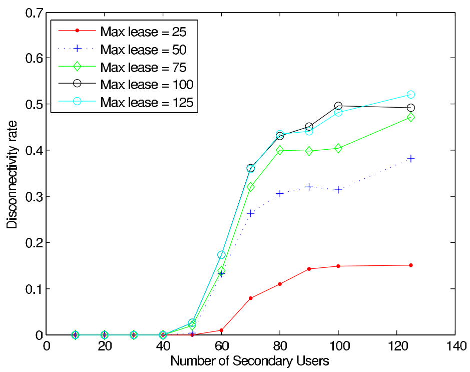

Fig. 9. Link connectivity for different Max lease period (PU arr = 5)

were carried out for different values of *max_lease* period to study connectivity and fairness. In Figure 9, it can be seen that the disconnectivity rate is lower for shorter lease periods. The larger values of lease period increase disconnectivity as SUs occupy channels for longer time and become more susceptible to PU channel reclaim. The shorter lease period has improved fairness in spectrum access but at the cost of higher communication overhead and highly dynamic network conditions. This study suggests the optimal *max_lease* period should be chosen to improve the fairness and connectivity with minimal overhead. The effect of different PU arrival rates on connectivity is also studied, with the simulation results presented in Figure 10. At lower PU arrival rate, shared spectrum is less dynamic and the connectivity is evidently better.

VI. Conclusion

This paper analyzes bidirectional and dual scanning mechanisms that expands search on multiple regions simultaneously in finding a suitable free-channel. The channel degradation and primary user arrival scenarios and how the proposed adaptive reserve channel and pointer mechanism maintains SU links are also considered. The simulation results of the proposed scanning method clearly show the ability to produce the closest free-channel without compromising complexity. Furthermore, the connectivity performance simulation results show significant impact of an adaptive reserve channel mechanism. Even

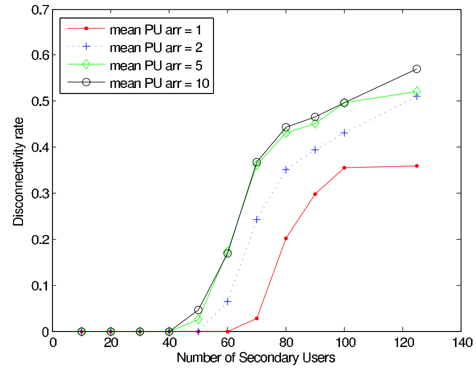

Fig. 10. Link connectivity for different PU arrival rate (Max lease = 100)

using an RC proportionality figure of 1% of channels the disconnectivity is improved by 77%. The parameters influencing connectivity and fairness such as *max_lease* period and PU arrival rate were also analyzed. The coordination among SUs and timing protocols can be considered in future work. The convergence rate of channel selection, and the dynamic characteristics of the link maintenance mechanism proposed can also be investigated further.

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